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## SEARCHING FOR EXTENSIONS TO THE STANDARD MODEL IN RARE KAON DECAYS

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### ABSTRACT

Small effects that are beyond the current standard models of physics are often signatures for new physics, revealing fields and mass scales far removed from contemporary experimental capabilities. This perspective motivates sensitive searches for rare decays of the kaon. The current status of these searches is reviewed, new results are presented, and progress in the near future is discussed. Opportunities for exciting physics research at a hadron facility are noted.

### INTRODUCTION

One day I was walking down the hall here at LAMPF and I saw one of these paintings, which have now become familiar to us all, of the AHF concept. There, in the experimental hall, Area A, was the detector I was then building at Brookhaven for rare-decay research with neutral kaons. One of the more furtive people here at LAMPF had complemented our collaboration by pre-installing us at AHF. I suppose this means that someday we will be allowed to bypass the Program Committee should such an accelerator be built. Alas, five years have elapsed, and the only item in the AHF complex which has been constructed is our detector. It is alive and well at Brookhaven and today I will use it to illustrate why building a hadron facility will open up exciting, new physics windows.

Is there anyone in this room who does not believe that the minimal standard model, as we define it today, will be modified or extended in the next decade? While I ask this rhetorically, I believe that I know the answer. Misguided or not, I believe the model will be altered, and that one can point at the most suspicious parts of the model as the likely candidates. Indeed, experimentalists engaged in this line of work must carry out this evaluation, or they will be mounting experiments aimlessly.

For most of us, testing the standard model leads to direct and enormous sieges at the colliding beam machines. Here one can directly probe the mass

scales and family structures, in certain ranges, which underlie the standard model, but which are not explained within it. The most suspicious parts of the standard model are the unexplained mass spectrum of the matter fields, the mystifying family structure of matter fields, and the Higgs mechanism, which is introduced to give mass to the gauge fields through spontaneous breaking of the local symmetry of the solutions to the theory. Experiments at colliders are direct, but limited in the energy range covered in the foreseeable future.

Of course there are other ways to address these pivotal problems. The work I will describe follows one of the great historical lessons of physics. Since I have only 15 minutes, or so, I will have to jump right into the middle of my subject. I will start in 1896.

## A HISTORICAL PERSPECTIVE

As you recall, Becquerel had this problem with film being exposed when placed in proximity to a piece of uranium ore. This observation set off a wave of experimental work around the world, dominated by Becquerel, the Curies, and Rutherford. In a matter of years, both alpha and beta radiation were identified and it became known that the transmutation which liberated the beta rays, responsible for exposing the film, appeared to violate the conservation of energy. Nearly a generation after Becquerel's original observation, Bohr was willing to consider abandoning this conservation law! Pauli, followed by Fermi, rescued the principle, by extending the very primitive notion of beta decay to include the emission of a light, neutral particle which carried the missing energy and balanced the books.

We all know the Fermi theory of beta decay. We recall that in the generation after that theory was proposed, it was extended to include the picture of a weak current carried by a charged boson. With the advent of the quark picture, this charged weak current coupled to the  $d$  and  $u$  quarks in the decaying nucleon. The boson carrying the neutral current was added to the picture, and this current was finally observed after yet another generation.

It was not, however, until 1983, almost a century after Becquerel's "unfortunate" film exposure, that the weak bosons were directly observed at CERN. Moreover, they were observed at a mass scale of  $10^{11}$  eV, while Becquerel was working on a scale of  $10^1$  eV. The spread between the observation of this "rare" decay and the direct observation of the underlying mass scale is 7 orders of magnitude!

The lesson for experimentalists is to pay careful attention to small effects from beyond the current state of knowledge. As in the case I have cited, they can be a vestige of physics at an inaccessible mass or energy scale. This is the

moral converted into action by those of us searching for rare decays of kaons or muons.

## PHYSICS MOTIVATION FOR RARE DECAY RESEARCH

How does this work in practice? I can't review all of the physics motivations for rare-kaon-decay experiments in this brief talk, but I can pick a simple model to illustrate the motif I have been advancing. Consider the family problem. In the minimal standard model, the quarks and leptons are organized into the well-known families, motivated by our observations of quark mixing, the hierarchy of masses, and some more technical considerations.<sup>1</sup> This organization is *put in*, but no rigorous or fundamental motivation exists. If the families reflected a true gauge symmetry, as in QCD or QED, there would be an exact conservation law. This law would correspond to a new force in nature and the theory would have to incorporate a massless vector boson, analogous to the photon in QED.

Such a scheme does not reflect observations. Families are mixed in the quark sector. The suppression of family mixing in the lepton sector may be a manifestation of a broken family symmetry. This would be the result of a massive neutral family vector boson. Such a model has been discussed by Cahn and Harari.<sup>2</sup> In Fig. 1, the diagrams for the conventional decay  $K^+ \rightarrow \mu^+ \nu_\mu$  and the lepton family non-conserving process  $K_L^0 \rightarrow \mu e$  are shown. The known process is mediated by the exchange of a  $W^+$ . The rare decay is postulated as resulting from the exchange of a neutral family vector boson. The couplings are indicated. By dimensional analogy between the two diagrams, and equating the analogous couplings, an estimate can be made of the mass of the family boson in terms of the rate or branching ratio for the process. The estimate is shown as

$$M_F = 24 \text{ TeV} \{1 \times 10^{-8} / B(K_L \rightarrow \mu e)\}^{1/4} \quad (1)$$

which involves a 1/4 power dependence of the mass on the sensitivity of experimental searches. I have expressed the formula in terms of today's approximate limit on this process. More revealing is a plot of this formula. Figure 2 shows how progressively more sensitive experiments in this area probe ever higher mass scales, though only for specific signatures. At  $10^{-10}$ , the mass scale is 75 TeV. This is an order of magnitude beyond the scale accessed at the SSC! This limit will be reached this year. The experiment I am going to mention shortly has as its goal sensitivities of  $10^{-11}$ – $10^{-12}$ . Masses of 135 to 240 TeV will be probed in this work! These arguments have been made for most of the interesting rare decays of the muon and kaon,<sup>1</sup> even though very different physical processes are

thought to be responsible. The good news is that most of these processes are currently being sought by experimentalists.

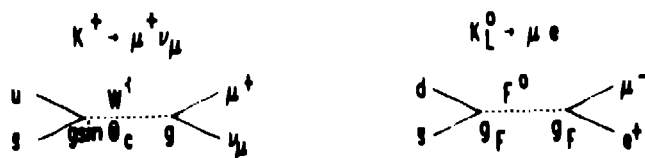


FIG. 1. Diagrams for the ordinary decay  $K^+ \rightarrow \mu \nu_\mu$  and the lepton-number non-conserving decay  $K_L^0 \rightarrow \mu e$ . The first reaction is facilitated by the  $W^+$ , the second by a possible neutral family-changing boson.

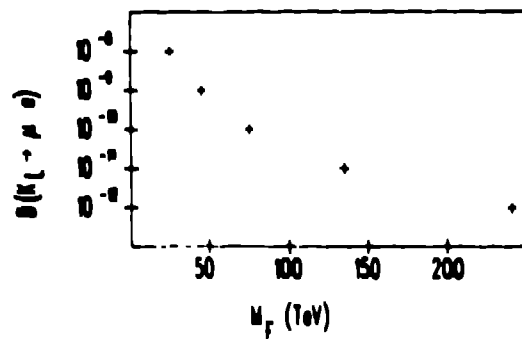


FIG. 2. The relation between the rate for the rare decay  $K_L \rightarrow \mu e$  and the mass of a family-changing boson, estimated using a simple dimensional analogy applied to the processes shown in Fig. 1.

## CURRENT EXPERIMENTAL STATUS

Since the progress in experimental sensitivity is so important, it is worth looking at the situation before the current round of searches begin to deliver results. Two years ago, the observed decay modes of  $\bar{K}_L$  were measured down to branching ratios as low as  $10^{-7}$  to  $10^{-8}$ , the latter being the GIM-suppressed flavor-changing neutral current  $\bar{K}_L \rightarrow \mu\mu$ . Branching-ratio upper limits on other processes were measured as low as  $10^{-7}$ . Many of these limits are changing rapidly now as a result of the large experimental effort mounted at Brookhaven and KEK.

Table I lists the current experiments and the goals of each effort. There are seven approved experiments now in this field. The first five have data. The last two are approved and constructing detectors. More than 150 experimenters are involved in total. This is equivalent to one of the large collider detector groups, with a set of physics goals covering a broad range (direct CP violation, lepton number non-conservation, familons, heavy neutrinos, neutrino counting, technicolor, supersymmetry, string physics, the Higgs spectrum, etc.).

TABLE I  
RARE KAON DECAY EXPERIMENTS—1988

1. BNL 780 (BNL-Yale)	$K_L \rightarrow \mu e$	$10^{-10}$
	$K_L \rightarrow e e$	
	$K_L \rightarrow \pi^0 e e$	
2. KEK 137 (KEK-Tokyo-Kyoto)	$K_L \rightarrow \mu e$	$10^{-11}$
	$K_L \rightarrow e e$	
3. BNL 791 <sup>†</sup> (UCLA-UCI-LANL...)	$K_L \rightarrow \mu e$	$10^{-12}$
	$K_L \rightarrow e e$	
	$K_L \rightarrow \pi^0 e e$	
	$K_L \rightarrow \mu \mu \uparrow$	
4. BNL 777 (Yale-BNL-SIN)	$K^+ \rightarrow \pi^+ \mu^+ e^-$	$10^{-11}$
5. BNL 787 (BNL-Princeton-TRIUMF)	$K^+ \rightarrow \pi^+ + \text{"nothing"}$	$10^{-10}$
	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	
6. BNL 845 (BNL-Yale)	$K_L \rightarrow \pi^0 e e$	$10^{-11}$
7. KEK	$K_L \rightarrow \pi^0 e e$	$10^{-11}$

#### A NEUTRAL-KAON-DECAY SEARCH

I would like to use our own experiment (BNL 791<sup>†</sup>) to illustrate how such a search is carried out, to show you some data and to tell you what to look for as the mature results emerge in the next several years. I shall, therefore, concentrate on the search for rare decays of the neutral kaon, and for the decay  $K_L \rightarrow \mu e$ , in particular. Figure 3 shows a generic "kit" for studying neutral kaon decays. The kit divides into three functional sections. The first, a neutral beam, separates charged secondaries from a production target with a set of magnets, and defines the remaining neutral component with a series of precision collimators. This system has been the bane of many experiments, with poor shielding, improperly aligned collimators and a ferocious neutron dominance over neutral kaons.

The second functional section consists of an evacuated decay volume for the candidate kaon decays viewed by a precision magnetic spectrometer. The spectrometer must track the decay daughters and provide a precise measurement

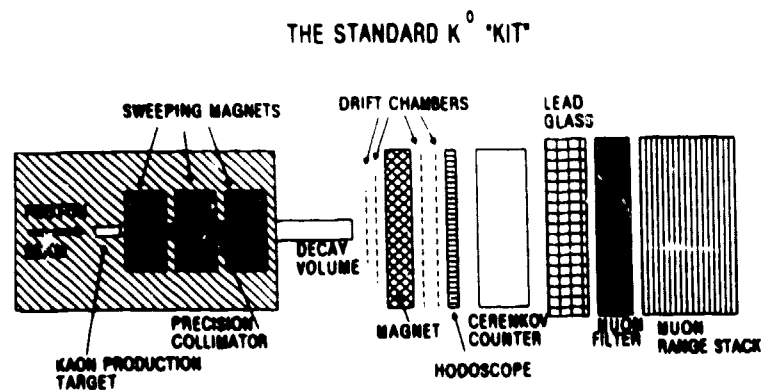


FIG. 3. A generic "kit" of detectors for a neutral kaon decay study.

of the track angle and momentum to facilitate reconstructing the parent invariant mass. The key features here are magnetic field strength for momentum analysis, and precise spatial resolution for the spectrometer detectors. The ability to handle high rates and the requirement of low detector mass are also paramount. Remember too, that the neutral beam survives along the spectrometer and it must not be allowed to confuse the instrument.

The third functional system consists of particle identification detectors. In order to identify the decay final states, clean identification of the pions, muons and electrons is required. Even more important is the elimination, to a very high sensitivity, of any misidentification of particle type. This is of key importance in eliminating backgrounds to these searches. We shall return to this point.

In our own experiment,<sup>4</sup> we have attempted to make very few compromises in the design of these systems. Figure 4 shows an artist's conception of what is now constructed and operating. The neutral-beam section is not shown, but I will say that it is the most successful implementation of such a beam to date. The capability to view the kaon production target as close as one degree to forward, the halo-free collimation, the shielding of the charged-particle dump and the suppression of leaking neutrons have all worked very well. Our beam has met most of our requirements.

The spectrometer improves upon past practice in a number of important ways. The neutral beam passes between the two arms, sacrificing some acceptance in exchange for quiet detectors, free from interactions from the approximately  $10^{10}$  neutrons per second passing through the experiment. The decay volume is long, and the exit window is not massive. The upstream detectors are precision drift chambers, without significant mass. This combination yields precise measurement of the decay-particle trajectories. The most significant feature is the double measurement of the particle momenta by the



## SOME RESULTS

We should finish this discussion with a look at some data. This is important because it will illustrate what to look for as ever more sensitive reports appear in the next few years. It is also important because these preliminary data already represent a very significant advance. In searching for the decay  $K_L \rightarrow \mu e$ , the struggle is to separate a possible signal from all of the possible sources of background. As I have already indicated, proper identification of particle types and accurate measurement of the decay kinematics are the needed capabilities for this separation. After track-finding, kinematic fitting, and application of the particle identification criteria, the surviving candidate events are plotted in a way which permits this background rejection.

Figure 5 displays a fraction of our data from the common CP-non-conserving decay  $K_L \rightarrow \pi^+\pi^-$ . The axes shown are the invariant mass of the particle pair versus the square of the "colinearity" angle between the two-body direction and the line between the kaon production target and the kaon decay point. A perfect example of this decay would fall within the kaon mass peak and have a colinearity angle measured to be zero. A background event from a random coincidence or an event with another decay would have a kink in the angle and an invariant mass shifted away (almost always down) from the mass of the kaon. The distribution of events shown in Fig. 5

displays the clustering of events from the desired decay, which defines the experimental resolution in these two key parameters. The sum total of all such events calibrates the sensitivity of the search because the branching ratio for this decay is well known ( $2 \times 10^{-3}$ ).

Another known, but quite rare, decay is the GIM-suppressed process  $K_L \rightarrow \mu\mu$ . The branching ratio is  $9.1 \times 10^{-9}$ , based on three experiments which collected a total of 27 examples. A preliminary plot of most of our recent data for this decay is shown in Fig. 6. The signal is clear, and totals approximately 80 events in the sample shown. The signal regions in Figs. 5 and 6 define the search region in the analogous plot for  $K_L \rightarrow \mu e$ .

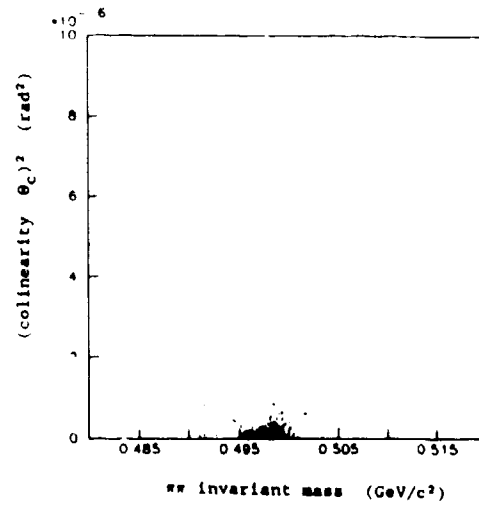


FIG. 5. The distribution in  $m$  and  $\theta_c^2$  of a sample of decays  $K_L \rightarrow \pi\pi$  from recent data of experiment 791. The clustered events are the actual signal.

Figure 7 shows the preliminary distribution of  $K_L \rightarrow \mu e$  candidates. The search region defined by the previous figures is empty. From the  $\pi\pi$  sample, and our knowledge of the detector efficiency for different-final-state particles, this establishes a preliminary limit on the lepton number non-conserving process of  $3 \times 10^{-10}$  (90% confidence level). This is far below previous limits. Using the simple dimensional arguments summarized in the formula presented earlier, this corresponds to a search for a flavor-changing boson up to masses of approximately 58 TeV!

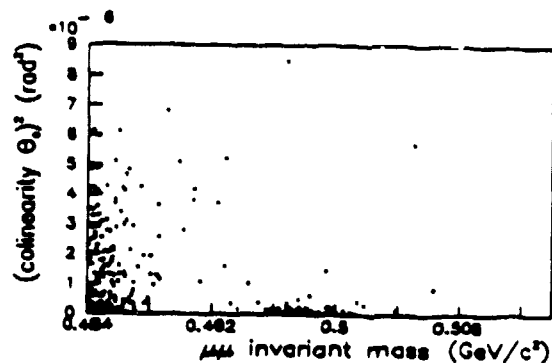


FIG. 6. A similar distribution for  $\mu\mu$  events.

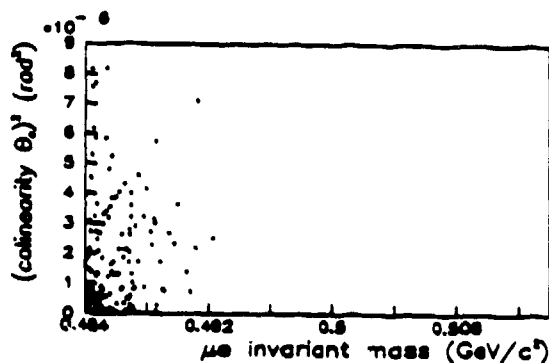


FIG. 7. A similar distribution for  $\mu e$  candidates. The signal region contains no candidate events.

## CONCLUSION

In the next several years we can expect to see substantial improvement in these searches, from our own experiment and the others cited in Table I. Currently five experiments are vigorously collecting and analyzing data. Figure 8 summarizes the progress made in the last five years, in which sensitivities of  $10^{-7}$  or so have been pushed to the  $10^{-10}$  or  $10^{-11}$  level for several reactions. The figure also shows my prediction for the  $10^{-12}$  achievable at the AGS, with a booster. Beyond that, a new hadron facility will be required

to push to the bottom of the chart. Some of the physics opportunities are shown. It is clear that this is an active and exciting field of research with much offered in the future. Indeed, it brings to mind the oft quoted words...

"I have to keep going, as there are always people on my track. I have to publish my present work as rapidly as possible in order to keep in the race...."

These are not the words of a contemporary kaon experimenter, but are taken from a turn-of-the-century letter of Rutherford's as he struggled with the rare decays of uranium.

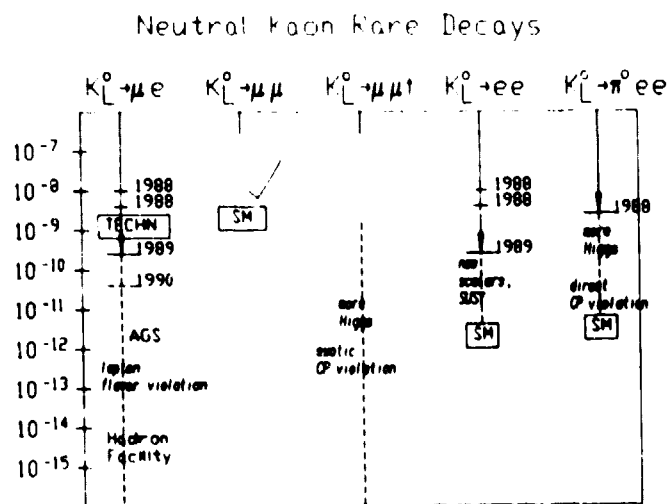


FIG. 8. Recent and future progress in neutral kaon rare decay research.

<sup>†</sup> Experiment 791 is a collaboration of the University of California, Irvine, University of California, Los Angeles, Los Alamos National Laboratory, Stanford University, Temple University, College of William and Mary, and University of Texas.

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